HETEROGENEOUS SENSOR NETWORKS: A BIO-INSPIRED OVERLAY ARCHITECTURE

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1. ARMY IMPACT

Sensor networks need to provide timely and accurate information about events on the ground to the dismounts and upper echelons in support of the mission and operations. Current unattended ground sensors (UGS) can provide accurate (local) temporal detection of events, but do not provide adequate performance in identifying objects from multiple sensors via the fusion of disparate sensor data. The Army needs timely dissemination of relevant information in the form of classification of terrestrial events, occurrence times, their trajectories and direction of movement of adversarial activities.

The Army currently employs heterogeneous UGSs using a sparse deployment to maximize coverage, minimize pilferage and to monitor terrain bottlenecks. The Army Research Lab (ARL) is moving towards an architecture (Family of UGSs) that will standardize communications (e.g. Blue Radio) and this will help to mitigate the heterogeneous UGS network problem. The Institute for Collaborative Biotechnologies (ICB) program is developing and will demonstrate a new system of bio-inspired software algorithms for autonomous operations that will leverage proven research to monitor heterogeneous UGS networks from extended ranges, that will collect data in a timely fashion, that will collaboratively control the motion of a sparse network of collectors (e.g. UAV's) using bio-inspired strategies, that will localize and synchronize communications, that will accurately detect and localize field events and will fuse and classify sensed data from UGSs using methods from Evolutionary Computing. The program will also provide both laboratory and field demonstrations of these capabilities supported through ARL by leveraging available resources.

1.1 TECHNICAL RESEARCH OBJECTIVES

Teledyne Scientific & Imaging (TS&I) in cooperation with ARL and the University of California at Santa Barbara (UCSB) have formed a team and have identified specific problem areas associated with automated data exfiltration and the generation of intelligence from multiple unattended ground sensors (UGS) using a sparse network of collectors (e.g. Uninhabited Air Vehicles or UAVs).

This paper will provide an overview and preliminary technical results from the following key areas of research being conducted on the project with emphasis on bio-inspired strategies leveraged from ICB research activities:

1.1.1 BIO-INSPIRED METHODS FOR UAV PLANNING AND EVENT DETECTION

This project will feature three bio-inspired technologies developed by the ICB at UCSB in collaboration with the ARL and by TS&I: (1) The navigation algorithms used by the team of collector UAVs to move among the UGS collection sites is based on data-driven stochastic search algorithms that were design based on the principles behind bacterial chemotaxis (Figure 1). Such algorithms exhibit low computational requirements and are able to avoid traps caused by local minima that arise often with data driven navigation. (2) The timing synchronization algorithms (discussed in more detail below) are inspired by swarming behavior observed in bird flocks and fish schools. These algorithms make optimal use of local information (peer-to-peer clock offsets) in estimating global parameters (absolute clock) in the same fashion that school of fish achieve coherent motion based on interactions between individuals. (3) Evolutionary algorithms are used to fuse sensor data from multiple UGSs for event classification.

1.1.2 UAV/UGS TIME SYNCHRONIZATION AND GEO-LOCATION

The UGSs monitoring a given area of interest may not be synchronized in time, and may not be in communication with each other. However, correlating sensor observations across space and time are crucial to fusing their data. We are therefore exploring *implicit* collector-based timing synchronization: UGSs report time-stamped data as well as their current time when reporting to the UAV, and the UAV uses its own clock as a reference when fusing data from multiple UGSs. We are also exploring scenarios where the UGSs' locations (again crucial for sensor fusion to localize events of interest) may be *a priori* unknown. We are exploring methods for using multiple UAV collectors flying in a closed-loop controlled formation to form virtual arrays to provide such localization. The notion of 'time synchronization' here should be interpreted as a metaphor for network parameters or functions of parameters for which there agreement among the sensors (UGSs) in the network.

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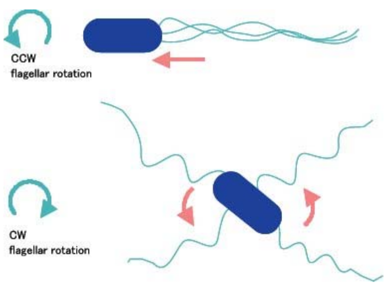

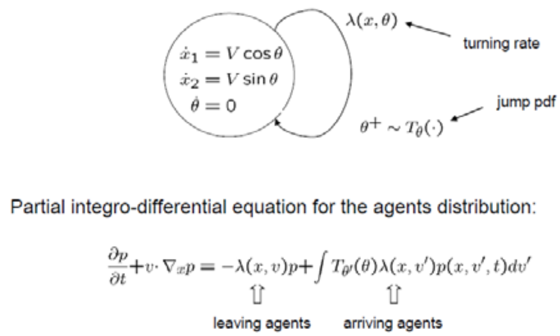

Figure 1A: Swimming behavior in Escherichia Coli. Fairly straight motion arises when the flagella rotate counter clockwise. When the flagella rotate clockwise, the motion of the bacteria exhibits a random change in direction.

Figure 1B: Stochastic hybrid system (SHS) model for the tumble-and-run motion used by E. Coli. The partial integro-differential equation below the SHS describes the time evolution of the probability density function for the position of the bacteria *p*.

1.1.3 EVENT LOCALIZATION AND CLASSIFICATION

Algorithms for fusing data from multiple UGSs to estimate bearing and location of field events have been developed for a sparse number of distributed sensors. The solution solves a non-convex quadratic programming problem that is NP (non-polynomial) time hard. In addition, bio-inspired techniques are being investigated to identify events from data collected by a sparse set of heterogeneous sensors; field data provided by ARL is being used to test algorithm performance. We are also exploring methods for mining data gathered from the sensor field for new, yet un-modeled events, by exploiting the correlation between the readings from different UGSs. A critical issue is to model and understand the impact of the *network* on the data / information collected / processed by sensors nodes and collectors.

2. DISCUSSION

In discussions with ARL, the ICB team has assessed the state of the art in the use of battlefield sensor networks and data exfiltration, which can be summarized as follows: sensor networks in support of current military operations are deployed with relatively few high-value sensors; the collection of data from these assets is intermittent, and not as timely as desired. Moreover, the quality of interpretation of data needs improvement. The primary cause of these deficiencies are non-standard heterogeneous UGS designs, infrequent visit times to these assets result in possibly stale information, and that the algorithms employed in UGS for sensor fusion and event classification maybe inaccurate and/or uncertain.

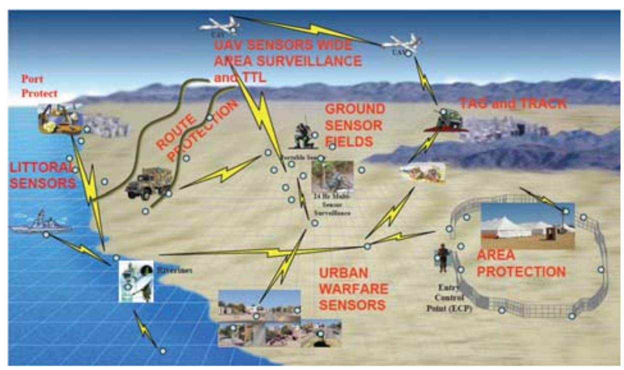

Figure 2: High level depiction of the deployment and interaction of unattended ground sensors in a battlespace; in this scenario, a sparse network of collectors (UAVs) are employed to capture and disseminate information to dismounted soldiers and local area echelons; problems identified include control of the collector network, communications with heterogeneous UGS networks and the accuracy and timeliness of event classification and tracking in the field.

In order to address the aforementioned Army needs, a program was funded by the Army Research Office under the ICB initiative. The specific technical objectives that will be addressed in the program and transitioned to the US Army are as follows:

- Provide significantly enhanced methods to detect, capture, fuse, classify and disseminate terrestrial events from a sparse network of collectors and unattended ground sensors using bio-inspired technologies

- Demonstrate the proposed capabilities via simulation, laboratory experiments and actual field tests; assess performance using well defined metrics and compare/contrast to the current approach used by the US Army
- Establish a collaborative effort between the University of California at Santa Barbara, ARL and Teledyne Scientific & Imaging to help develop a concept-of-operations relevant to US Army operations and define the necessary software algorithms and hardware implementations needed to demonstrate new and novel capabilities; provide accurate and timely situational awareness to both dismounted solders in the area of interest and to upper military echelons using available US Army applications and assets
- Leverage current research to demonstrate how revolutionary improvements can be achieved for controlling a network of collectors to optimally cooperate, collaborate, detect and capture data from heterogeneous sensor networks; strategies will be based on how bacteria search for nutrients in an environment and collaborate via attraction/repulsion to optimize their ability to localize and synchronize their behaviors; show how a global search optimization problem can be solved over a distributed topology using bio-inspired methods that avoid local minima
- Demonstrate how aerial collectors can significantly extend their detection range using low level (low duty cycle) signals from existing UGSs
- Substantially improve the fusion capabilities of current sensors/collectors using methods associated with evolutionary computing; demonstrate how data captured from individual UGSs and their sensor suites can be effectively combined to provide accurate classifications such as differentiating between specific events that are currently confused (lightning, gun shots, mortar launch, explosions, etc.); demonstrate how data captured from multiple UGSs can be fused to provide improved classification and situation awareness
- Define and pursue a plan to transition the end technologies to the US Army in a timely manner; identify potential customers within the US Army (e.g. AATD and CERDEC)
- Leverage related research and activities being supported in complementary programs such as ITA and CTA.

2.1 BIO-INSPIRED METHODS FOR UAV PLANNING AND EVENT DETECTION

At the ICB, UCSB has been investigating stochastic bio-inspired decision algorithms to control the motion of networks of artificial mobile agents involved in surveillance/target-tracking missions that overcome many of the challenges previously mentioned (Hespanha, 2007). We start by describing the optimotaxis motion control algorithm that UCSB has devised to allow a network of agents to find the maximum of a spatial function, based on point measurements collected at their present locations. We then discuss how this algorithm can be adapted to solve the UAV data collection problem.

2.1.1 OPTIMOTAXIS

The motion of the bacteria Escherichia coli is characterized by periods of fairly straight motion (runs) interleaved by random changes in direction (tumbles), as shown in Figure 1A.

The regulatory pathways that control the frequency of tumbles have been extensively studied. This study revealed that the frequency of tumbles is controlled by the *gradient* in the concentration of repellents and chemical attractors. In particular, the frequency of tumbles remains small if the bacterium is moving along a direction in which the concentration of attractor's increases and the concentration of repellent decreases. However, tumbles become very likely when the bacterium moves in directions along which concentration of attractors decreases or the concentration of repellents increases. This algorithm results in an effective stochastic search mechanism that only requires point measurements for the concentration of the attractive/repellent chemical agents that makes use of mobility to effectively determine gradients across these concentrations.

The stochastic hybrid system in Figure 1A can be used to model the tumble-and-run algorithm. Prior results allow us to write a partial integro-differential equation that describes the time evolution of the probability density function *p(.)* for the position of an agent (Hespanda, 2007). To develop efficient algorithms for search and detection one needs the probability density function *p(.)* to reflect the relevant spatial variable.

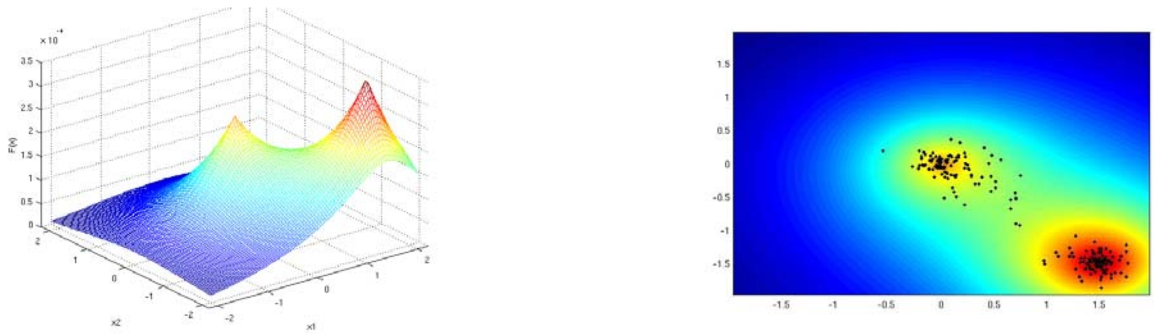

Figure 3: (left) Value (z-axis) of a spatial variable defined over a 2 dimensional (x-y axis). (right) Spatial distribution of a group of agents (black dots) according to a probability density function that reflects the value of the spatial variable: agents appear mostly concentrated near the maxima of the variable, with the largest concentration at the global maxima. The spatial distribution of the agents is used to estimate the value of the spatial variable.

In particular, if the goal is for the team of agents to find the source of a chemical plume, then the maximum of *p(.)* should occur near the point where the concentration of the chemic agent is maximal, since this will guarantee that the agents will (with very high probability) find the location of the maximum (Figure 3).

The plot at the right of Figure 3 was obtained by using a turning rate λ(.) for the tumble-and-run stochastic hybrid model in Figure 3 that gives rise to an agent distribution that mimics (up to a scaling factor) the value of the spatial variable of interest. As in small bacteria, only point measurements are needed and the vehicles do not require knowledge of absolute position. It is important to emphasize that the bio-inspired algorithm designed by the PIs to produce the agent's distribution in Figure 3 is very robust with respect to disturbances and measurement errors, which is not surprising in view of the fact that bacteria have evolved this algorithm for such environments.

2.1.2 Bio-inspired Data-Driven Data Collection

The technical approach for the design of the motion control algorithm for the UAVs is also inspired by the tumble-and-run algorithm. Essentially, UAVs will travel from UGS to UGS following straight-line paths[1]. However, at any point in time, the UAVs may decide to perform a "tumble" maneuver, which in this case means that they will change their course. Tumbles will be stochastic, with the probability of tumble increasing as it becomes more likely that the destination UGS has no useful information to send, or that another UAV is better positioned to collect any data that may be available. This form of bio-inspired stochasticity has two important benefits: it prevents the system from becoming trapped in local minima (without requiring a combinatorial search) and it results in algorithms that are very robust with respect to fault, measurement errors, and disturbances.

There are three key differences between the data-driven data collection problem and the optimotaxis algorithm that was previously described:

1. In optimotaxis, the decision to tumble was based on local measurements of a spatial variable. Due to the agents' motion, these local measurements actually provide information about the *gradient* of the function. For this system, the decision to tumble will be based on the perception that a particular direction that the collector is moving towards will lead to the capture of important data. However, the selected direction will still be driven by local information available to the collector.
2. The spatial location of the UGSs will often be known to the collector UAVs. This means that a UAV's direction change due to tumbles does not need to follow a uniform distribution in a 360 degree range. Instead, they should be (stochastically) biased towards the directions of known UGS with high potential to have important data. If the scenario involves UGSs at possibly unknown locations, one should still allow for some probability of motion towards a direction other than those of known UGSs.

[1] Deviation from straight paths may be necessarily if the terrain or other considerations (such as no-fly zones) constrain the UAVs' motion.

3. In optimotaxis, one wants a larger concentration of agents in regions of space close to the maximum of a spatial variable. However, now there is generally no need for several UAVs to visit a particular sensor, even if this sensor has very important data. As discussed below, biology provides the needed inspiration to overcome this challenge.

In bacteria like E. coli, stochastic decisions to run and tumble are employed not only to determine movements for individual cells, but also for the creation of multi-cellular structures. It has been recently shown that E. coli secretes chemo-attractants that are used as signaling mechanisms to form clusters. This is achieved by adjusting the tumble frequency of each individual, depending on their location within the cluster, thereby controlling the morphology of the cluster. In essence, the cells themselves produce clues for chemotaxis, making certain locations more attractive than others.

In bio-inspired data-driven collection, we want to avoid situations in which several collectors simultaneously attempt to collect data from the same UGS. This can be achieved by basing the stochastic tumbling decisions not only on attractive hints that a particular UGS has useful data, but also on repelling hints produced by other collectors. These hints will be supported by RF communication, instead of the chemical communication used by bacteria.

2.2 UAV/UGS TIME SYNCHRONIZATION AND GEO-LOCATION

The location of existing high-value sensor assets is typically known *a priori*, being noted at the time of deployment. However, in many future combat scenarios, we envision soldiers deploying lower-cost sensor assets in the battlefield on an ad hoc basis, and GPS may be unavailable due to a hostile RF environment (e.g., in a mountainous terrain such as Tora Bora, or in urban canyons) or due to active jamming. In such scenarios, the UAV collector network must also be responsible for localizing the sensor, in addition to collecting data. There are a large number of localization techniques in the literature; they are based on information such as time-of-arrival (TOA), time-difference-of-arrival (TDOA), received signal strength (RSS), and angle-of-arrival (AOA). RSS techniques are often quite unreliable because of fading, delay spread and shadowing, while TOA and TDOA methods require accurate synchronization. AOA techniques require that the collectors be equipped with antenna arrays.

We are currently developing AOA-based localization algorithms with multiple stationary collectors. These can be leveraged and extended to localization using UAVs. If a UAV has a directional antenna, then it can estimate the AOA of the signal from a sensor at any given time instant. By collecting multiple AOA measurements when it is in different positions in its flight path, a single UAV can emulate multiple stationary collectors, and use the algorithms being developed at UCSB to estimate the sensor's location. We will develop algorithms for controlling the flight path so as to quickly arrive at an accurate estimate. Multiple UAVs can collaborate for quicker localization using such AOA methods, which can also be combined with RSS methods in a specific fashion. Collaboration between multiple UAVs can be used to increase convergence time or accuracy. For TDOA methods, it becomes essential to use multiple UAVs: the problem to be addressed is that of accurate time synchronization between UAVs so that TDOA methods are accurate, as well as control of their flight paths during the localization period. Low cost sensors are likely to have inexpensive clocks, and as such will require frequent resynchronization (offset and skew); this is particularly critical when nodes are duty cycled. Given that UAV's are also energy-constrained, the tradeoff in energy expended for UAV control for coverage vs. synchronization will be studied. The sensing capability of UGSs may also be exploited; for example, the UAV could transmit an acoustic signal, and at the same time a radio signal with this acoustic signal, so as to provide a benchmark for signal processing. If the UAV transmits its coordinates, a few measurements corresponding to different points on the UAV trajectory will suffice for multiple sensors to simultaneously synchronize and localize themselves. If the sensors are not acoustic sensors, other modalities may have to be investigated.

2.3 EVENT LOCALIZATION, CLASSIFICATION AND DISCOVERY

The concept of operations outlined by ARL consists of a sparse sensor network laid out over a 5-10 Km^2 area where only a small number of UGSs will be able to detect an event of interest. Event *localization* refers to a system capability to fuse data from multiple UGSs for the purpose of estimating the location of a detected event. In addition, event tracking over time is also needed along with capabilities to handle both the near and far field problems. Event *classification* refers to deciding what the event is (e.g., tank treads, explosion), typically from among a database of events of interest. Event *discovery* is a term we have coined for adding to, or creating, a database of interesting events for which prior models may not be available. For example, even if the acoustic signature of a particular vehicle is not in our database, we should be able to detect and estimate its signature from the readings obtained by multiple UGSs.

Event Localization: With five or more UGSs detecting an event, estimating the location of an event can be solved in a number of known ways (Floudas, 1995). However, when the number of UGSs that detect an event is below five, then the problem becomes increasingly hard; in fact, the general problem has been shown to be a non-convex quadratic programming problem that is NP (non-polynomial) time hard. This means that it may require substantial computational resources to solve the problem (if a solution exists) in a reasonable time frame to support operational environments.

During the first year of the ICB program, TS&I obtained real world data from ARL that depict a sensor network consisting of 5 UGSs observing an explosive event at far range (~2 Km). TS&I researched the problem of event localization when only 4 or 3 UGSs observed the event. Time synchronization is required between UGSs.

With four UGSs, the problem of event localization can be solved by reducing the problem to a 1-D parameter search. Good results were obtained for this case. Figure 4 shows some Monte Carlo simulation results for the case of four sensors; the study measures the average radial error for event localization vs. the standard deviation of random range (time difference of arrival) errors at each UGS. Confidence bounds (95%) are shown for each level of range error. The results of these Monte Carlo simulations show that good performance can be achieved for event localization for the four sensor case.

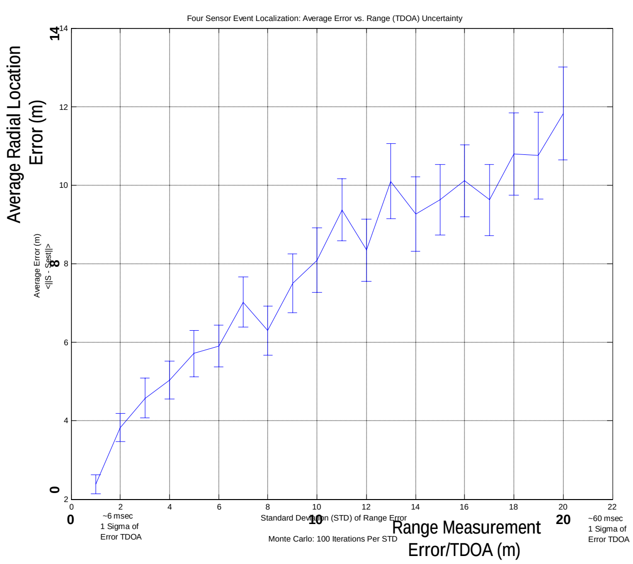

Figure 4: Monte Carlo simulation results with confidence bounds (95%) for the average radial location error vs. the standard deviation of the range or TDOA measurement error (UGSs) for the four sensor case.

When three sensors detect an acoustic event, the problem complexity is substantially increased. The problem involves a 2-D search over a very complex surface to find a global minimum with many local minima. Figure 5 illustrates the challenge associated with searching a complex surface for a global minimum which represents the solution to the event localization problem. TS&I investigated a number of published techniques including the MatLab Optimization kit and methods that have won international competitions (e.g. Price, 2006) in optimization contests with little success in reliably estimating the location of events for three UGSs. As mentioned previously, the problem is NP hard and solution feasibility is a significant factor. That is, determining whether or not a solution exists for a specific geometry and TDOA error is required.

Fortunately, TS&I discovered a very recent paper (Beck, Stoica, 2008) that reduces the 2-D problem to a 1-D search. TS&I enhanced the algorithm by adding additional logic to speed up the search process which involves many matrix inversions and to determine when a specific geometry does not admit a feasible solution. Monte Carlo simulations were conducted using this enhanced method for the three UGS problem and very good results were obtained. Figures 6 and 7 show the accuracy of the method and the probability that a feasible solution can be found.

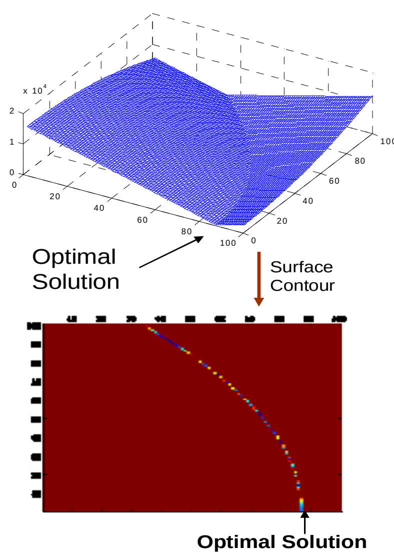

Figure 5: 2-D surface that needs to be searched to find global minimum which represents the solution to the event localization problem; this problem is NP hard because the surface contains many local minima.

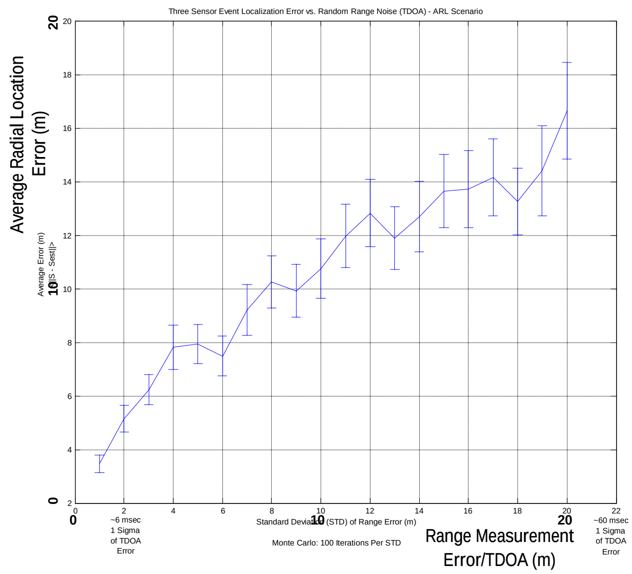

Figure 6: Monte Carlo simulation results with confidence bounds (95%) for the average radial location error vs. the standard deviation of the range or TDOA measurement error (UGSs) for the three sensor case using the enhanced Beck/Stoica algorithm.

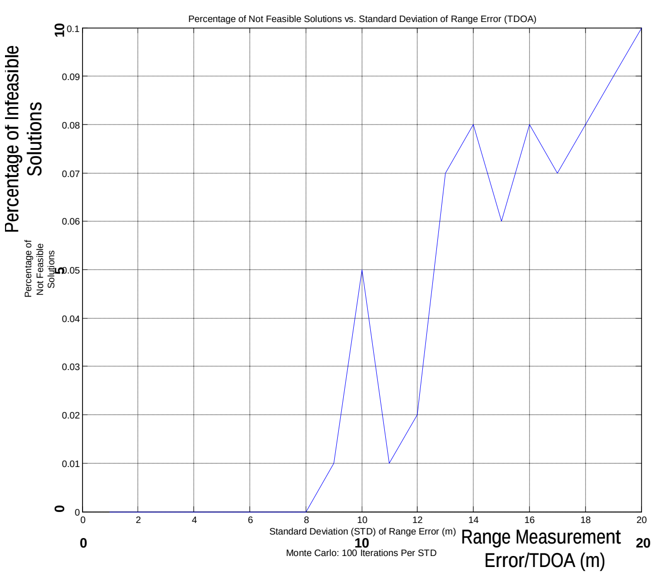

Figure 7: Monte Carlo simulation results for the percentage of infeasible solutions vs. the standard deviation of the range or TDOA measurement error (UGSs) for the three sensor case using the enhanced Beck/Stoica algorithm.

The results of the Monte Carlo simulation studies showed that for the four UGSs case, the average radial localization error was about 4 m for 6 msec of TDOA error (standard deviation) and about 12 m for 60 msec of TDOA error which is very good event localization performance (Figure 4). Moreover, for the three UGSs case, the modified Beck/Stoica method showed an average radial localization error of about 5 m for 6 msec of TDOA error and 17 m of radial error for 60 msec of TDOA error also representing excellent performance given the complexity of the problem (Figure 6). The probability of an infeasible solution for the three UGSs case was very low for up to 24 msec of TDOA (standard deviation) and reached about 10% for 20 m or 60 msec of TDOA error measurement (Figure 7). Moreover, the method was also tested against the near field problem and showed excellent performance. In addition, the computational time to find a solution was reduced to less than one second in MatLab. The overall results show that the event localization problem can be reliably and accurately solved for the difficult case of only three UGSs.

Event Classification: TS&I also obtained additional data from ARL that will be used for event classification. The data represents explosive events, gunshots and other types of events of interest to the Army. The approach being pursued by TS&I to classify these events is currently being researched and will use bio-inspired methods based on evolutionary computing. The results of these investigations will be available at the end of 2008.

Event Discovery: Given a sparse deployment of UGSs in the field, the signal-to-noise ratio (SNR) with which an actual battlefield event is detected may be poor for all the sensors monitoring the event. Furthermore, not all event reference signatures may be stored in the sensor database. Can we detect an interesting event without having a prior model for it, especially at low SNR? The human sensory system routinely accomplishes this task by building up a database of interesting events through experience. One approach to mimicking this success through a network of UGSs is to exploit the correlation between the sensor observations: if we do not have a prior event model, we can exploit the correlation among the observations for different UGSs; in this way, it may be possible to detect a similar event and estimate its signature. We have obtained promising preliminary theoretical and experimental results with this approach at UCSB (Venkateswaran,, Madhow, 2008) showing that, even at low SNR, it is possible to detect and estimate signals based on observations at multiple sensors, even without time synchronization. Figure 8 shows sample simulation results: the first plot shows a noiseless acoustic signature, the second shows the noisy observation at one sensor, while the third shows the estimated acoustic signature waveform based on observations at 20 sensors; each sees a very noisy version of the acoustic signature through a different delay. The sensors do not have a prior

model for the acoustic signature. Rather, they detect that there is an interesting event by the fact that their observations are correlated (as opposed to uncorrelated "quiet times"), and they then estimate the event's signature by pooling their observations.

We are currently working on experimental validation for microphone sensors for both indoor and outdoor environments. UCSB intends to leverage a recent DURIP award, which will enable us to instrument parts of the campus with camera and microphone sensors. A key technical challenge in merging sensor observations is that each sensor sees the event signature through a different dispersive channel. However, analogous to wireless communication using Orthogonal Frequency Division Multiplexing (OFDM), one can process the observations in the frequency domain, exploiting the fact that each channel can be modeled as constant over a frequency bin smaller than the coherence bandwidth. We initially had difficulties with stitching together observations from different frequency bins, but resolved them recently by drawing bio-inspiration from the human auditory system, whose “front-end” consists of a bank of heavily overlapping narrowband filters (instead of the orthogonal frequency bins used in OFDM). By heavily overlapping the frequency bins in similar fashion, we are able to stitch together the observations effectively. We will continue to leverage the human auditory and visual systems, with the first step consisting of the design of heavily parallel and redundant front-end processing.

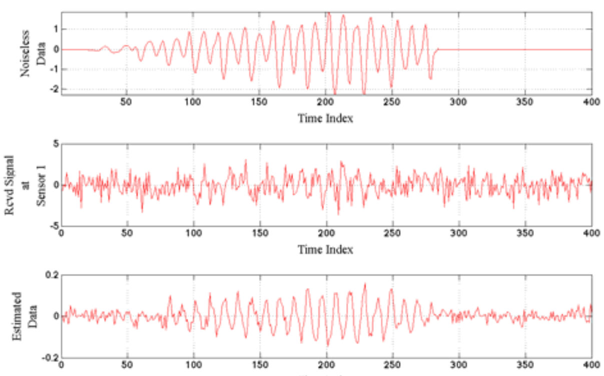

Figure 8: Event discovery by pooling observations from multiple sensors; one can extract the event signature even when each sensor sees a very noisy observation.

3. CONCLUSIONS

UAVs provide an effective means to autonomously collect data from a sparse network of UGSs. In addition to providing a communication infrastructure and a mechanism for implicit synchronization of sensors, they can also be used to reduce the system reaction time by using data collection routes that are data-driven. Bio-inspired techniques for search will provide a novel strategy to detect, capture and fuse data across heterogeneous sensor networks.

The enhanced method from Beck/Stoica can be used to reliably estimate the location of an acoustic event given three or more sensors by solving a complex non-convex quadratic programming problem that is NP hard. The method reduces the problem to a 1-D search. In addition, the method is fast and will indicate if a solution exists. Moreover, the approach develop under this effort is accurate, tolerant to noise in the sensor measurements, can track an event over time and handles both the near and far field problems. The benefit to the Army is a reliable method that can be easily implemented on-board the collector (UAV). It also can provide timely and accurate geo-referenced information for situation awareness for dismounts (e.g. consistent with FBCB2).

Finally, the bio-inspired event discovery techniques which we are developing will enable fusion sensor observations at low SNR without requiring a prior model for the event signature; this is a first step towards sensor networks that are capable of learning. Concrete demos for detection and estimation of interesting events using microphone sensors are planned under an ICB 6.2 project. Bio-inspiration from the human sensory system will first guide front-end design for these systems, but we ultimately hope to draw upon better understanding of higher layers of processing in the brain to guide our design of the fusion logic.

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